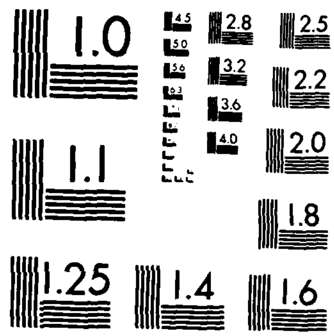
AD-A171 716 COMMAND-AND-CONTROL (C2) THEORY: A CHALLENGE TO CONTROL SCIENCE(U) MASSACHUSETTS INST OF TECH CAMBRIDGE LAB FOR INFORMATION AND DECISION SYSTEMS M ATHANS JUL 86 1/1

UNCLASSIFIED LIDS-P-1584 N00014-77-C-0532 F/G 17/2 NL



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July 1986 Contract N00014-85-K-0782 LIDS-P-1584

AD-A171 716

COMMAND-AND-CONTROL (C2) THEORY: A CHALLENGE TO CONTROL SCIENCE.

by

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0. SUMMARY

The basic premise of this position paper is that the field of military Command-and-Control (C2) systems offers challenging basic research opportunities to researchers in the control sciences and systems engineering disciplines. In point of fact, the analysis and design of complex, survivable, and responsive C2 systems requires novel advances in the area of *distributed dynamic decision-making under uncertainty*. As a consequence, control scientists and engineers are uniquely qualified to extend their technologies to meet the multidisciplinary challenges posed by C2 systems and to advance the state of the art in the development of a relevant C2 theory.

The author strongly believes that the methodological, theoretical, algorithmic, and architectural questions which arise in the context of military C2 systems are generic and quite similar to those needed to improve the reliable performance of many other civilian C2 systems, such as air traffic control, automated transportation systems, manufacturing systems, nuclear reactor complexes etc. All such military and civilian C2 systems are characterized by a high degree of complexity, a generic distribution of the decision-making process among several decision-making "agents", the need for reliable operation in the presence of multiple failures, and the inevitable interaction of humans with computer-based decision support systems and decision aids; also, they require the development of novel organizational forms and

system architectures which provide for the harmonious interface of the mission objectives associated with the C2 process and the physical hardware, such as sensors, communications devices, computer hardware and software, and effectors -- weapons or machines -- which implement the overall Command, Control, and Communications (C3) system whose purpose is to support the global C2 decision process.

Military C2 systems provide one particular focus for the development of a whole new class of control/estimation/decision technologies - technologies which share the intellectual roots of current research in the control sciences, but which can grow and blossom into methods applicable to a very large variety of civilian complex systems.

In the remainder of this paper we shall concentrate upon military C2 processes and C3 systems, since they provide the most stringent performance requirements and because they exhibit the greatest clear-cut need for quantification of their measures of performance (MOP's) and measures of effectiveness (MOE's), and the requirement for novel distributed architectures and organizational forms. The discussion will undoubtedly reflect the personal bias of the author who has studied and researched military C3 systems over the past decade, in the sense that the objectives of a military C2 system are easier to pin down, and the need for survivable/reliable operation with minimal communications is transparent. However, it is the strong personal conviction of the author that any technological advances in the state of the art in military C2 systems are readily transferable to civilian C2 systems.

1. TWO MILITARY C2 SYSTEMS

1.1 Introduction.

In this section we overview two different Battle Management C3 (BM/C3)systems. One relates to the defense of naval Battle Groups, while the second addresses issues related to the Strategic Defense Initiative. The former involves a significant component of tactical human decision making, while the second is envisioned to act in an automatic tactical mode. The author has studied both of these in some detail. Many other BM/C3 systems involving Army, Air Force, and Marine operations involve similar issues. Our objective is to set the stage for the types of issues which are important in C2 systems, so that later on we can isolate certain generic questions common to them. These in turn will define the broad opportunities in which basic research in the control sciences and system theory can extend its applicability.

1.2 The Defense of Naval Battle Groups.

A naval Battle Group (BG) is defined as consisting of at least one carrier (CV) together with several escorting platforms (ships, submarines, and aircraft). The CV's and their platforms contain a wide variety of sensors and weapon systems which allow the BG to carry out defensive and offensive missions as prescribed by higher authority.

The defense of the BG assets is clearly of paramount importance. The threat to the BG is multiwarfare in character. The BG threat consists of enemy submarines, which can launch long range missiles and/or short range torpedoes, surface ships which can launch missiles and/or cannon projectiles, and aircraft that also launch missiles and/or conventional bombs. As a consequence, the defense of the BG involves antisubmarine warfare (ASW), antisurface warfare (ASUW), and antiair warfare (AAW); electronic warfare (EW) permeates the BG operations as well. The enemy platforms must be detected using information from organic BG sensors perhaps "fused" together with information gathered by other national assets; they must also be identified, tracked and engaged (hopefully) before they launch their offensive weapons against the BG assets.

The BG defense involves several layers. Obviously, enemy submarines, ships, and aircraft must be engaged before they can launch their long range missiles; this is often called the "outer battle". "Area defense" against aircraft and missiles is provided by missile-shooting platforms (the newest one being the Aegis class cruisers). "Terminal defense" involves individual platform weapons, such as rapid-fire guns and/or short-range missiles, and different countermeasures (jamming, decoys etc) that are designed to confuse incoming weapons.

The vulnerability of the BG platforms to enemy weapons, especially nuclear ones, forces wide geographical dispersal of its platforms. Also, long-range submarine detection requires certain platforms to operate at the fringes of the BG formation. Thus, it is not unusal for a multicarrier BG to have its platforms spread-out over hundreds of miles. The large geographical dispersal of the platforms makes it difficult to communicate with each other, using line-of-sight communication frequencies, while escaping enemy detection of the communication signals that help localize the BG location and denying the enemy the detection of certain unique electromagnetic emissions that may reveal the identity of certain platforms. Hence, survivability considerations must be traded-off with the need to communicate so as to coordinate the BG defensive operations.

At present the U.S. Navy also operates under a *distributed* C2 doctrine, the so-called Composite Warfare Commander (CWC) doctrine which reflects the complexities of Naval warfare and survivability. The senior admiral in charge of the BG (CWC), under the CWC doctrine, can delegate command and control

authority and responsibility to three senior warfare commanders: the ASW commander (ASWC), the ASUW commander(ASUWC), and the AAW commander (AAWC) who are specialists in their respective warfare areas. It is not unusal for these subordinate commanders to be located in different platforms so as to improve survivability anc :o have direct access to unique sensor data and/or weapon systems. The CWC assigns control of specific platforms (submarines, ships, aircraft, helicopters etc) to each subordinate warfare commander, a resource-allocation problem, so that each one can defend the BG assets from the specific threat in his assigned domain.

Although the CWC doctrine appears to be reasonable at first glance, it requires intensive coordination, and hence reliable communications, among the CWC and his warfare commanders due to several reasons. The first reason is that an enemy submarine (or surface ship) that has survived prosecution by the ASWC (or the ASUWC) will launch its missiles and these missiles become the AAWC's problem. Thus, the AAWC must position his assets in such a way so as to be able to engage surviving submarine and surface ship launched missiles. The second reason relates to the fact that most naval platforms have sensor and weapon resources that are useful in several warfare areas; thus, a destroyer under the control of the ASWC may still be a very valuable platform for the AAWC. The third reason relates to BG electronic warfare (EW); the assets for EW are spread among most platforms, and the superior coordination of the EW assets, at the global BG level, remains an unsolved problem. The Navy, aware of this problem, has assigned an EW coordinator - not a commander - to advise the CWC in EW related matters.

1.3 Battle Management C3 in the Strategic Defense Initiative.

The Strategic Defense Initiative (SDI) offers extraordinary challenges in the Battle Management C3 (BM/C3) area. Long-term SDI system architectures envision a multilayered defense system against ICBM's and SLBM's. Potentially enemy weapons are engaged in the boost, post-boost, early midcourse, late midcourse, high endoatmospheric, and low endoatmospheric phases by a variety of orbiting and ground-based weapon systems. Different sensors reside in diverse satellites in different orbits, as well as in airborne and ground-based nodes. Orbiting weapons may include X-ray lasers, chemical lasers, fighting mirrors to direct ground-based free electron lasers, electromagnetic launched weapons, orbiting kinetic-kill vehicles etc. Ground based weapons may include free electron lasers, and kinetic-kill vehicles such as long-range and short-range missiles.

Clearly the direction of the weapon systems must rely upon the BM/C3 functions of detection, tracking, discrimination (i.e. weapon or decoy?) and damage assesment information provided by both orbiting and ground-based sensor systems. This multi-sensor information must be fused and mapped into the weapon-to-target

assignment and engagement control functions. The distribution of the BM/C3 decision processes is dictated not only by orbital mechanics, but even more by severe survivability requirements, so that the SDI system can survive significant enemy attacks by ASAT weapons.

Leaving socio-political considerations aside, the SDI has been criticized in terms of the feasibility of its huge BM/C3 software requirements, since the tactical system will have to operate in an automated mode simply because there is no time for humans to evaluate the huge amounts of sensor information and to arrive at superior weapon engagement strategies in the short time available (about 30 minutes). The critics (many of whom are computer scientists) are addressing in the author's opinion the wrong problem. The challenge is rather a control-theoretic one: *how to properly design the distributed algorithms that implement the diverse BM/C3 functions, so that a prescribed degree of reliability and survivability is maintained.* Although we do not have all the theories as yet, it is the author's belief that many available results in large-scale estimation, optimization, and control are directly relevant and applicable to the SDI BM/C3 problem. On the basis of available results one could argue that, given sufficient research, control theorists and engineers can develop the required survivable and reliable distributed architectures and algorithms which will implement the SDI BM/C3 estimation, optimization, resource allocation, and control algorithms.

2. SOME GENERIC ISSUES IN MILITARY C2 SYSTEMS.

2.1 Introduction.

Altough each military BM/C3 problem has its own unique set of mission requirements and physical assets, nonetheless all C2 systems have a great degree of commonality. *It is precisely this generic commonality that offers the hope that the development of a relevant C2 theory will have a significant impact upon the analysis and design of military C2 systems.* A little thought should convince the reader that the command-and-control of several complex civilian systems also involves similar generic issues.

In this section we discuss what are the major high-level problems in military C2 systems. We focus, in particular, to issues related to organizational forms and distributed decision architectures. These are precisely the areas that offer the most fertile ground for basic and applied research by control scientists and engineers; these will motivate the more detail listing of relevant interdisciplinary basic research areas in the sequel. We remark that any analysis tools that help quantify the expected performance of existing C2 organizations, as well as of synthesis methodologies that help in designing new superior BM/C3 architectures are

desparately needed.

2.2 The Impact of Geography.

A military C2 system is a multi-agent organization. The decision agents are both human decision-makers and computer-based algorithms. The decision agents are geographically dispersed due to environmental and survivability reasons. Geographical dispersion is dictated by the environment, the nature of sensors, and the physics and speed of the weapons. Thus, both geography and vulnerability contribute to the distributed architecture of C2 organizations. Such geographically motivated decompositions define, for example, the multiple defense tiers in the BG defense and in the SDI scenarios. Each defense tier can be further decomposed into sectors, although protocols for hand-over coordination and need for low-level communications present thorny issues.

Geographical distances interact with the speed of the weapons, the range of the sensors, and the tempo of the military operations in the definition of defense tiers, defense sectors etc. It is important to realize that any technological developments that impact sensor ranges, weapons speeds, etc must be reflected into a reorganization of the C2 system in order to maintain superior performance. This may necessitate doctrinal revisions as well as changes in the architecture of the BM/C3 system.

2.3 Functional Decompositions and Distributed BM/C3 Architectures.

Another key element that contributes to the way the C2 process is organized has little to do with geography. The C2 process can be decomposed into a set of generally accepted *C2 functions* that must be executed (sometimes serially and sometimes in parallel and, in general, in an asynchronous manner) to ensure mission success. This list of functions related to defensive Battle Managment C3 is as follows:

(1).*Threat Detection*, based on data from several sensors.

(2).*Target Tracking*, based on data from several sensors. This function may involve 2-dimensional tracking by individual sensors and fusion into 3-dimensional tracks. Sensor cueing, scheduling and control is an integral part of this function.

(3).*Discrimination*, which results in the resolution of true threats from decoys often requiring the fusion of data from several (active or passive) sensors. Sensor cueing, scheduling and control is also an integral part of this function.

(4).*Identification*, the process by which further identity information of threats is established.

(5).*Battle Planning*, the process by which decisions are made on how to deal with the identified threat, based on (1) to (4) above, including contigency planning.

(6).*Weapon-to-Target Assignment*, the set of decisions which lead to the assignment of one or more weapons to engage each threat, including the assignment of any necessary sensor, communication, and other resources required for each and every one-on-one engagement.

(7).*Engagement Control*, the process by which the decisions in (5) and (6) are executed in real time.

(8).*Damage Assessment*, the process by which one identifies and/or verifies the outcome of the engagement, i.e. whether a particular target has been killed.

The above list of BM/C3 functions have to be executed at a global level, at a defense tier level, at a sector level etc. The so-called *BM/C3 architecture* reflects how these functions are implemented by the sensor, computer, communications, and weapon hardware and where the *BM/C3 algorithms*, which realize these functions and are executed by human commanders and/or computers, are located. It is obvious that the vulnerability of the humans and hardware that implement the BM/C3 functions, i.e. *the vulnerability of each and every BM/C3 function*, is a very strong driver to the physical distribution of the decision agents; this leads to the problem of first analyzing candidate *distributed BM/C3 architectures* and later on the design of C2 organizations which implement the distributed BM/C3 architectures in a superior manner. Ideally, the survivability of each function to enemy attacks and to environmental phenomena calls for some redundancy; exact replication should be avoided if at all possible.

2.4 The Impact of Complexity.

The decomposition of the C2 decision processes is also influenced by the complexity of the warfare problem. This is, in general, true when simultaneous engagements involving heterogeneous sensor and/or weapon systems can take place, and human commanders make a large part of the decisions. For example, the BM/C3 decision process for the defense of a Battle Group falls in this category. Different commanders are trained to be "specialists" in different warfare areas, although they may have to share, and compete for, many common resources. No commander alone can deal with the inherent complexity of the global engagement; this leads to a decomposition of the decision process along distinct "expertise" dimensions.

In such C2 organizations team training is essential so as to achieve superior coordination and to make best utilization of scarce common resources. Indeed, it has been observed that in well-trained teams the decisions of individual commanders are

different than those that the same commander would make if he were to operate in isolation (see Sections 3.4 and 3.5 for additional discussion).

At an abstract level, one can model the decomposition of the C2 process along specialist dimensions as yet an alternative way of decomposing the generic BM/C3 functions.

2.5 Discussion.

At present, all analysis and synthesis studies related to distributed BM/C3 architectures are carried out in an ad-hoc manner; it is self evident that the development of quantitative methodologies, theories, and algorithms relevant to the distributed BM/C3 architecture problem would be welcomed by the defense community. *It is interesting to note here that the C2 community does not, in general, appreciate the intimate relationship of distributed decision-making algorithms that execute the BM/C3 functions, their tactical communications requirements, and their intimate relation to distributed BM/C3 architectures.*

It is generally acknowledged that *centralized* BM/C3 hierarchical architectures are very vulnerable, introduce possibly unacceptable time-delays, yet are efficient in resource-utilization. At the opposite extreme, it is also realized that *autonomous* architectures (those that operate in a purely decentralized mode with no tactical coordination whatsoever) are more survivable, require minimal time-delays, but are most inneficient in the use of scarce resources. Obviously, *distributed BM/C3 architectures* are the answer, somewhere between centralized and autonomous ones. The difficulty is that there are an infinite number of ways that one can think of designing distributed BM/C3 architectures, and no general guidelines are available on how to even get started!

In short, superior BM/C3 architectures must be distributed in both a geographical and a functional sense, taking advantage in an integrated manner the impact of geography, functional decomposition, mission objectives, problem complexity and the survivability of the BM/C3 functions. Current C2 technology approaches all of the above problems in a completely intuitive and qualitative way (maybe this is the reason that Artificial Intelligence salesmen have had funding success). As a consequence, there does not exist even a systematic methodology that can be used to understand in a precise manner the complex cause-and-effect relationships inherent in a C2 process and to describe them using a minimal set of primitives, measures of performance, and measures of effectiveness. Clearly control scientists and engineers can have an impact in this key area.

There is no fundamental reason whatsoever which inhibits the emergence of a quantitative methodology that addresses, in a relevant manner, the challenging BM/C3 architectural problems. Indeed, one can argue that the strong relationship of

the nature of the distributed algorithms that implement the BM/C3 functions, which make strong use of control-theoretic concepts (variants of hypothesis testing, Kalman filtering, mathematical programming, stochastic optimization, etc), and of distributed BM/C3 architectures provides a natural starting point in the quest for a C2 theory. *Engineers and scientists trained in control theory and operations research, and related normative disciplines, are uniquely qualified to develop the needed basic research for distributed BM/C3 systems.*

3. A BASIC RESEARCH AGENDA.

3.1 Introduction.

In this section we outline some basic research directions that appear to be relevant in the quest for a C2 theory. Needless to say, there is no claim that the suggested research directions are all inclusive. However, it should become self-evident that these research directions are in the spirit of the evolving research traditionally associated with control science and engineering. The control science field broadened its research horizons into decision-oriented problems more than fifteen years ago when we started studying "large-scale systems". What we call C2 theory requires advances in control/estimation/decision technologies along particular dimensions to support our basic understanding of the BM/C3 processes and their reliable and effective implementations.

3.2 Understanding a Complex C2 System.

Before we can even analyze, never mind design, a C2 system we must first understand it. In order to understand it, a common representation language and a hierarchy of models must be developed which are useful in the sense that the key variables, transformations of these variables, and measures of performance become transparent.

Such C2 representation tools are not currently available. Block and functional-flow diagrams are used to indicate interconnection of physical devices, but these are not sufficient to capture the information flow, the sequence of events, the essential precedence relationships, and the time delays that are so crucial.

Some very recent attempts, which show some promise, are based on extensions of the *Petri Net* methodology originally developed to model digital computer operations. The extension of the Petri Net methodology to model BM/C3 systems requires the assignment of attributes to the Petri Net tokens, stochastic decision rules, time delays, and nonconcurrent events. Such extended Petri Net methodologies appear useful because they can help isolate the truly independent

variables (analogous to a minimal state-space realization), keep track of the information and physical variables that must be present before a particular decision can be executed, account for stochastic time-delays associated with the implementation of the decision process, and capture probabilistic outcomes of the decisions. Such extended Petri Net methodologies also blend well with finite-state representations. Further, they can be used to study the C2 process in terms of its basic generic BM/C3 functions (see Section 2.3), allowing for a certain freedom to the C2 analyst in controlling the level of aggregation and the degree of detail appropriate for the questions posed. They also resemble the discrete-event dynamic models being used to describe manufacturing systems.

3.3 Modeling C2 Systems.

At a very detailed level the state variables underlying any C2 system are both continuous and discrete; hence, so-called *hybrid* state-spaces must be studied. The dynamic evolution of the state variables can be modeled in discrete-time; however, there does not exist a fixed time interval (such a sampling time) that governs the evolution of the state variables. Rather, we deal with *event-driven* dynamical systems and state-variable transitions occur at stochastic times that are, in general, asynchronous. Hence, modeling methodologies that are "tied" to a time-synchronization model are not apt to be either relevant or useful. Therefore, *problem-driven research related to hybrid, event-driven, asynchronous stochastic dynamic systems is of interest, especially when the state transition probabilities also depend on the values of not only certain exogenous variables, but also on a subset of the state variables.*

The difficulty with a hybrid state approach to modeling complex C2 systems is the huge dimension of the underlying state space. Although such fine detail may be necessary to construct an event-driven microscopic Monte-Carlo simulation (which may require well over 100,000 lines of FORTRAN code), such large-scale microscopic simulations (several of which have been constructed for specific military problems over the years) are time-consuming, expensive, and not well suited for analysis, design, and evaluation of alternate distributed BM/C3 architectures.Also, "what if" questions are costly to answer using these huge simulations. Indeed, a major shortcoming of many of the existing large scale simulation models is that the C2 process is not modeled in a way that tradeoffs associated with different BM/C3 architectures can be carried out. *This brings up the research need for systematic aggregation methodologies that result in higher level models that, hopefully, approximate the microscopic interactions and are more suitable and ameanable to analysis and design.*

Few aggregated models exist, and even these have some significant limitations. The so-called *Lanchester Equations* of combat, a set of nonlinear differential equations that model mutual attrition of opposing forces using different types of weapons,

have been widely used by the military community. However, it is very difficult to incorporate in the Lanchester-type equations the impact of different distributed C2 organizational forms. *The development of high-level models that capture not only attrition, but explicitly incorporate decision variables that relate the impact of alternative C2 organizations would be highly desirable, because one could then, in principle, analyze, synthesize, and optimize the BM/C3 architectures.* Ideally, these aggregate models should have their roots in the microscopic hybrid-state models so that their predictions can be checked by detailed Monte-Carlo simulations. It would be very useful to develop aggregation methodologies for this class of systems, with transparent advantages and shortcomings.

Another set of important modeling-oriented questions relate to the evaluation of aggregate measures of performance (MOP's) and measures of effectiveness (MOE's). In optimal control jargon, MOP's involve functions of output variables that have a specific meaning and are important to a military decision maker; think of combinations of different MOP's as defining the integrand of the cost-functional in a dynamic optimal control problem. Similarly, think of MOE's as corresponding to a particular cost functional which integrates over time a weighted combination of the MOP's. *One of the most important MOP's in any C2 system relates to the time delays associated with the execution of the generic BM/C3 functions,* such as detection, tracking, discrimination etc (see Section 2.3). The reason is that the performance of a BM/C3 system is like a race against time between the moving physical entities (targets, sensors, weapons) and the information variables. In a well designed BM/C3 system the information variables must win the race; the detection function must be completed before either the tracking and/or the discrimination functions can commence, and targets must have been sorted, identified, and tagged before we can wisely commit weapons against them. Delays in execution of any of these functions may degrade the kill probability, result in inneficient use of battle space, cause weapons to be assigned to decoys rather than threatening targets and/or assign too many weapons against the same target, and perhaps allow many targets to leak through a particular defense zone.

There exist significant and challenging opportunities in developing large-scale models that quantify delays for a given BM/C3 architectures; the availability of these models would allow the C2 analyst to pinpoint bottlenecks which would point the way for modification of the BM/C3 architecture. Delays arise from a wide variety of phenomena, e.g. signal processing of sensor data, other computational delays, communications delays in fusing information, and decision delays associated with human or algorithmic decision-making. It appears that significant extensions to the available theory associated with queueing networks are necessary in order to faithfully describe the elemental and global time-delays associated with a particular BM/C3 architecture.

To appreciate the relevance of queueing theory think of a target as being a

"customer" in a service queue; a C2 node must service the target in the sense of performing a BM/C3 function (e.g. detection, tracking, engagement, etc). In a proactive BM/C3 system a specific C2 node may be assigned to perform the appropriate function. Since the target is moving, there is only a finite time-window of opportunity to service this target; otherwise, the target will leave (leak) that particular C2 node. Thus, we have to deal with *queues with reneging*. Although some theoretical results are available in this class of queueing network problems, additional research is required to arrive at an expanded set of theoretical results, together with efficient computational algorithms, to faithfully model the delays in a BM/C3 system.

Another important basic research area deals with the extension of classical queueing theory to capture transient effects. Classical queueing theory deals with steady-state phenomena. In many military scenarios the steady-state assumption is often violated. At present, such transient phenomena can only be handled by microscopic simulations, and these are difficult to interface with a classical queueing network model. Any theoretical developments that help simplify the interface of static and transient delay models are very relevant and useful. If we develop theories and algorithms that allow the C2 analyst to evaluate easily both steady-state and transient delays, then one would also be able to use such queueing network models to study the vulnerability of the BM/C3 system to enemy countermeasures (jamming, node destruction) at least from a delay viewpoint.

3.4 Modeling Human Decision Makers in C2 Organizations.

In present C2 systems, almost all of the BM/C3 functions discussed in Section 2.3 are executed by trained human commanders; there are very few computer-based decision aids in use today. Since a C2 system involves the integration of humans with physical assets (sensors, communication links, weapons, etc), it is self evident that in order to analyze the performance of a C2 system one needs some high-level mathematical models that abstract the decision-making process of trained military commanders. In the absence of such models one can only rely upon very very expensive field exercises and war games; these are valuable and necessary, but their cost precludes the answering of too many "what if" questions. In particular, *current military expertise does not necessarily carry over without significant training to situations in which technological advances yield new sensor and/or weapon systems.* To put it another way, technological breakthroughs in sensors and/or weapons may require a drastic reorganization of the BM/C3 architecture in order to realize the benefits of these "high tech" hardware. It is not obvious that even a top-notch commander, trained under an older doctrine and within a different C2 organization,will perform at his best, say, in a war game that incorporates the novel "high-tech" devices.

A most pressing research topic is the development of "normative/descriptive"

models of human decision-makers operating in a geographically dispersed and distributed tactical BM/C3 architecture environment. The term "normative/descriptive" is used here to stress that the mathematical models of human decision makers should be based on nonclassical optimization based formulations, which explicitly include constraints that reflect human cognitive limitations, the impact of workload, and the protocols associated with the C2 organization.

Distributed detection, estimation, optimization, and organizational design problems with communications constraints (topics which we shall discuss more in Section 3.5) result in *normative/ prescriptive* solutions; they define superior ways that a team of "agents" should map their nonclassical information patterns into decisions, thus providing a prescription for the optimal team behavior. *Such normative/ prescriptive models are very useful for providing paradigms and help to design experiments by cognitive psychologists which can pinpoint in what precise sense trained human decision makers, and the organization as a whole, deviate from the predictions of normative/prescriptive models and solutions.* Experimental results should then provide "empirical/descriptive" models of individual and organizational decision making. The next challenge is to blend the outcomes of the normative and of the empirical research, using the insight provided by the empirical/descriptive models to introduce additional constraints in the original normative formulation. The new "hybrid" solution, termed normative/prescriptive, should yield far better mathematical models of team human decision making and of the performance of the organization as a whole; note that these "hybrid" mathematical models can be used for predictive purposes in subsequent BM/C3 modeling and analysis studies.

Control scientists and engineers can assume a leadership position in this fascinating research area. First, the development of normative/prescriptive models, theories, and algorithms for distributed decision making is a subject of research that has received attention (not enough!) by researchers in the large-scale systems area. Second, control scientists have pioneered the development of mathematical models that can adequately predict the behavior of a human operator in carrying out a well-defined task, so that we do have a reasonable past success record in this area. Third, although there exist many basic research results by cognitive psychologists in modeling the "bounded rationality" of human decision makers, there are no results, at present, in the psychology community that address the types of problems inherent in the distributed tactical decision making environment which is typical in military BM/C3 problems. Therefore, the solutions of pure normative/prescriptive distributed decision problems, and the (often) counter-intuitive nature of the results, will be very valuable in the proper definition of the experimental designs to be carried out by cognitive psychologists. Some research efforts that use the tools of normative sciences (control theory, information theory, mathematical programming, etc) have shown very promising initial results in this area.

3.5 Distributed Situation Assessment.

The generic BM/C3 functions of target detection, tracking, discrimination, and identification (see Section 2.3) serve the purpose of providing a global picture of *situation assessment function* in the C2 process. Knowing in a timely and accurate way the identity and attributes of each and every target, as well as its current location and velocity, is essential in order to construct a list of possible alternative actions and decide on what seems to be the best one.

From a technology point of view, the situation assessment function falls squarely in the domain of modern control theory. Most of the basic research findings in optimal estimation theory, developed during the past twenty five years, have been applied to the situation assessment function with a great deal of success. It is perhaps surprising that there is still a great deal of basic research that remains to be done in order to implement the situation assessment function succesfully in complex BM/C3 systems.

The relevant research directions can be appreciated from the fact that in order to obtain a clear picture of the threat one must "fuse" information from several, possibly heterogenous sensors, which are geographically distributed, each obtaining data from a multiplicity of targets. Thus, *any relevant research in this area must address the generic problems associated with multiple sensors and multiple targets, including the fact that accurate estimation of both continuous(i.e. position) and discrete (i.e. identity) state variables is required.* Hence, the overall problem formulation must include a "hybrid" state space (see also the discussion in Section 3.3).

In multi-target problems we have the generic complexity that even when we are using a single sensor we do not have information over time regarding the matching of sensor measurements and targets. This phenomenon brings up the issue of *data association* which must be performed by the algorithm in addition to its classical detection and tracking function. Technically, this involves setting up a (rapidly growing over time) hypothesis-testing problem that necessitates judicious pruning of the resulting decision tree. The next class of problems often goes under the name of *multisensor correlation,* which requires the exchange of information among two or more sensors in order to improve the hybrid state estimate for a particular target, and this must be done for several targets at each and every instant of time. Since each sensor has a different hybrid state estimate trajectory for each target, the consolidation of information in the *multisensor fusion* problem requires the solution of another large-scale hypothesis testing problem. It should also be noted that identity information is often provided by specialized sensors (e.g. passive ESM receivers, active discrimination sensors) which more often than not have poor location accuracy. In short, it is highly nontrivial to design a superior BM/C3

architecture and associated algorithms that result in an accurate and timely implementation of the situation assessment function in a dense multi-target multi-sensor environment. It should be noted that the presense of multiple hypothesis testing algorithms in such BM/C3 decision structures can be exploited by digital computers with special parallel processing architectures.

The above discussion suggests that the hybrid state estimation problem and the associated large scale hypothesis testing algorithms are only a part of the research challenge. The multisensor fusion problem requires significant tactical communications among the sensors, and these communications are vulnerable to enemy intercepts and/or jamming. It is clear that some communication is necessary to arrive at a superior situation assessment; what is not clear is what is the minimally acceptable exchange of information. Perhaps, each sensor node should have the intelligence to transmit information only when it is clear that this communication is cost-effective. Conversly, each sensor should only transmit information only when requested; the intelligent sensor that requests information should be sure that the received information is worth the cost. It should be self evident that such information transmission options will have a significant impact of the architecture of the situation assessment function in the BM/C3 system. It should be noted that present BM/C3 architectures are notorious for trying to communicate everything to everybody.

The research problems become even more complicated and challenging if we assume that one or more sensor nodes can be destroyed, with some probability, by the enemy. In that case the algorithms that implement the situation assessment function must be distributed so as to improve the survivability of the situation assesment BM/C3 function. *At present we do not have a general theory, accompanied by algorithms, that addresses this class of problems. The development of such a theory will have a significant impact in BM/C3 problems, and will definitely impact the design of superior BM/C3 architectures which also exploit parallel processing in digital computers.* The theory promises to be highly nontrivial because it will require the solution of distributed team-decision problems, with nonoverlapping information patterns including incomplete "models of the world". To make matters worse, there is strong theoretical evidence that the underlying optimization problems are NP-complete; hence, we may have to be satisfied with suboptimal solution algorithms, accompanied however by guaranteed performance bounds.

In spite of their complexity, a very small number of distributed hypothesis testing and estimation problems have been solved during the past few years. Obviously these algorithms are valuable in their own right in automated situation assessment systems. However, the nature of their normative/prescriptive solutions has also provided valuable qualitative and quantitative insight into the decision rules of the completely rational "decision agents" operating in a distributed team decision

setting. Indeed, one can see in certain team solutions that the decision rules (mapping of local information into team decisions) of the same decision agent are *very different* than those that would have been employed if the same decision agent was operating in isolation under identical environmental conditions. Another set of valuable insights relate to the fact that in order for a team of decision makers to reach decision-consensus, based on different local information, tentative individual decisions must be communicated to each other with a quantifiable minimum communication frequency. *These findings reinforce the claim in Section 3.4 that the normative/prescriptive solution of distributed decision problems can have some impact in experiments carried out by cognitive psychologists, since from a purely mathematical point of view a perfectly rational decision maker uses different decision rules depending on whether he/she makes a decision in isolation or as a member of a team; such a change in the behavioral pattern, if observed, should not be attributed to the "bounded rationality" of the decision maker.Also, the nature of normative/prescriptive results can flag the monitoring of key observation and decision variables in the human team experiments.*

3.6 Distributed Battle Engagement.

Following the situation assesment function, the BM/C3 system must execute a sequence of real time decisions to implement its defense objectives against the threat. The Battle Planning, Weapon-to-Target Assignment, and Engagement Control functions (see Section 2.3) are the BM functions that implement the battle engagement.

Complex multiple weapon-target engagements have benefited somewhat from available theoretical results in mathematical programming and optimal control theory. However, these studies have been very problem specific and, more often than not, the problem formulations, algorithms and tradeoff studies are classified. To the best of the author's knowledge, there are no unclassified studies that pose these battle engagement problems in a generic setting, exploit the available state-of-the-art, and isolate the advantages and disadvantages of present solution methodologies so as to point out specific basic research directions for future work.

In this class of problems we are concerned with planning and executing several engagements of M weapons against N targets. The problem complexity is related to the different options available to the defense. The more options available to the defense, the harder the problem and the greater the potential payoffs associated with near-optimal decisions. Residual threat uncertainty also contributes to the complexity of the defense decisions.

Generic studies of battle engagement issues should include one or more of the following three types of defense weapons. The potential effectiveness of each weapon can be quantified by its idealized one-on-one kill probability.

(1)*One-on-many weapons*. Such weapons have the potential to kill several targets all at once. The X-ray laser, which focuses the X-ray energy of a nuclear explosion along several beams, is an example of such a weapon. Since such weapons can be very effective to the defense, their *commitment threshold* must be carefuly selected. The presense of such weapons within one or more defense tiers can force the offense to adopt a different offense strategy than simply a saturation attack.

(2)*One-on-one reusable weapons*. Such weapons can engage one target at a time, and must be sequenced over a subset of targets until they run out of resources. Different types of laser weapons (including orbiting mirrors) and machine-gun type weapons fall in this category. Note that such weapons must employ some sort of *target sequencing algorithm* to decide the order in which they should engage several targets. Optimal target sequencing algorithms must take into account the different times to lock-on to a target, to service it, and to slew it against another target.

(3)*One-on-one non-reusable weapons*. These represent classic one-on-one engagements. Missile interceptors fall in this class. Often, such weapons require additional guidance, and perhaps target designation/illumination, resources to hit their assigned target.

The physical characteristics of the defense weapons interact with the physical attributes of the targets, geometry, speed etc. Typically, a particular target has a finite time-window during which it can be succesfully prosecuted by a particular weapon. The decision to commit a particular weapon to that target must obviously take into account this time-varying target vulnerability. Relative target/weapon speed characteristics may require that the weapon-to-target pairing decision be made long before the target vulnerability window. Other strong temporal effects arise when the succesful intercept requires that the target be illuminated by a laser or radar for designation and terminal homing purposes.

One of the neglected areas of research relates to the coupling of the situation assessment and battle engagement functions. Almost all present studies assume that the targets have been localized and identified before weapons are assigned to them. It is very important to capture the residual uncertainty of the threat situation assessment into the very formulation of the weapon-to-target assignment problem. This is particularly important in the midcourse phase of SDI defense, where we must distinguish several thousand re-entry vehicles from many more thousands of decoys. The optimal use of battlespace may necessitate to tentatively assign missiles against targets that have not been fully discriminated. As time goes on, the discrimination function will improve the probability that a particular target is a real threat or a decoy, and there may be ways to divert a missile tentatively assigned to a decoy to engage a real thereat. We note that current practice enforces what is known to control scientists as the "certainty equivalence" principle in stochastic control

theory. The class of open research problems that we have discussed employ what is often called the "open loop feedback optimal" policy of stochastic control. Indeed these problems can become very complex if we assume that an active discrimination resource must be scheduled, as a function of time, over a set of targets. Then we must study the simultaneous optimization of the discriminator dynamic schedule and of the weapon-to-target assignment function.

It should be evident from the above discussion that, as a rule, M-on-N engagements have a highly dynamic flavor. Also, stochastic effects are dominant, since kill probabilities are nonunity. The decision variables are both discrete-valued (how many weapons should we assign to a particular target? which weapon should be assigned to what target?) and continuous-valued (when should we launch a particular interceptor? where should we intercept the target?). There may exist specific problem variants that require optimal use of battlespace; in this vein, the possibility of *salvage fusing,* which means that a target with a nuclear warhead explodes when intercepted, results in very challenging decision-dependent state-space constraints in the SDI scenario. Extreme care must be exercised to ensure that the planned intercept trajectories avoid the nuclear fireballs that follow salvage fusing. As a consequence, *stochastic dynamic optimization problems, with mixed integer programming overtones,* are present in most complex battle engagement formulations. In principle, such optimization problems can be formulated as stochastic dynamic programming problems with a high degree of combinatorial complexity. In order to obtain computable solutions one must exploit the structure of these problems, perhaps decompose them into a subset of simpler problems, and then develop algorithms that take advantage of the problem-specific information.

The study of complex M-on-N battle engagements are hard enough even when posed at a centralized level. *The scientific study of distributed battle engagement decision architectures is just beginning.* Presumably, over and above the problems associated with the existence of non-classical information patterns at each decision node, one must study the tradeoffs associated with the vulnerability improvement of the battle engagement decision function vis-a-vis possible misuse of scarce weapon resources (multiple targeting of the same target, targeting of the wrong target, etc). Any new results that provide quantitative insight in this class of problems will be very valuable indeed.

Relevant research in this area must explicitly recognize that the underlying optimization problems are almost surely NP-complete. Thus, there are numerous opportunities for designing novel near-optimal solution algorithms with guaranteed worst-case and expected performance bounds. The distributed version of the battle engagement problems provides fertile new research directions that blend architectural issues, decision-theoretic issues, and communication interfaces that carry the necessary coordinating information.

4 CONCLUDING REMARKS.

In this position paper we discussed, in an informal way, the nature of the research topics that we feel are essential ingredients of a general C2 theory. We need a variety of results that help us understand, analyze, compare, and synthesize BM/C3 systems. We stressed the need for incorporating vulnerability/reliability requirements which dictate the study of distributed decision-oriented BM/C3 architectures.

The roots of this research agenda are in the traditional discipline of control science and operations research. We need a hierarchy of modeling tools which help us understand and model, at different levels of detail and aggregation, complex BM/C3 systems. We need novel theoretical and algorithmic advances in the distributed versions of multiple hypothesis testing, estimation, and optimization problems, stressing nonclassical information patterns, costly communications, and explosive combinatorial complexity. The modeling and analysis of BM/C3 systems with interacting human decision makers poses special challenges in the development of "normative/descriptive" models of human decision makers operating in a team tactical environment. Finally, we need the development of methodologies that help integrate performance and vulnerability of BM/C3 functions and define superior distributed C2 organizations and BM/C3 architectures.

Control scientists and engineers have already pioneered the development of specific C2 quantitative models and analytical tools that improved past practices. These recent accomplishments, although modest, have had a significant impact on the way the military C2 community is thinking. Thus, the present climate is very favorable for basic research in this area, with good opportunities for transitioning basic research into advanced development. The control community is ideally qualified, from a technological point of view, to advance the state of the art in C2 theory.

The challenge relates to the way the basic research is conducted. It is the author's opinion that the major advances in C2 theory will be made by researchers who invest a great deal of effort and energy in understanding and appreciating the complexities and subtleties of military BM/C3 systems. We have stressed that although optimization problems abound, the research issues at a basic level have a very nontrivial combinatorial flavor. Hence, it is the intimate familiarity with specific pragmatic issues that will provide the essential guidance to the researcher on the development of near-optimal algorithms that solve inherently NP-complete problems. It is highly unlikely that the needed research breakthroughs can be *solely* based upon abstract extensions of current theory. It is also evident that collaborative research between control scientists, cognitive psychologists, computer scientists, and communications engineers is required to address the many important

dimensions of BM/C3 systems.

ACKNOWLEDGMENTS.

The author has benefited over the past decade from numerous discussions on research priorities and new directions in the area of C2 systems with several colleagues. Special thanks are due to A. H. Levis, J. N. Tsitsiklis, N. R. Sandell, D. A. Castanon, R. R. Tenney, J. G. Wohl, J. J. Shaw, L. C. Kramer, J. R. Lawson, S. Brodsky, C. Holland, J. R. Simpson, W. R. Vaughn, W. Meyers, D. L. Kleinman, M. Melich, J. Offut, J. Wozencraft, P. Girrard and W. B. Davenport.

The financial support of the Office of Naval Research under contracts ONR/N00014-77-C-0532, ONR/N00014-84-K-0519 and ONR/N00014-85-K-0782 is also greatfully acknoweledged.

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